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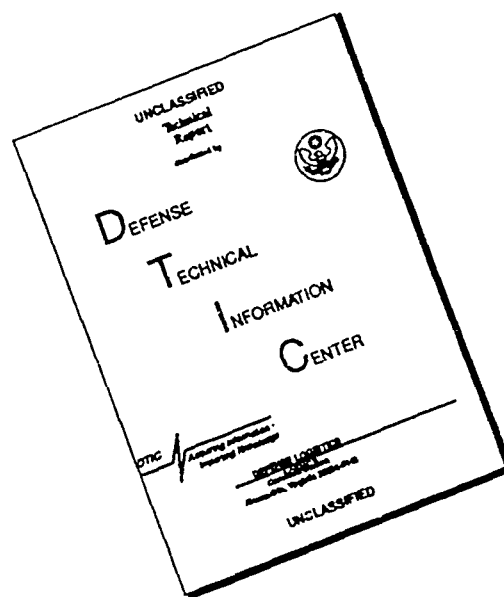## SCIENTIFIC AND TECHNICAL INFORMATION
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Reduction of Range Ambiguity in the Madre Radar

Final Report

[Unclassified Title]

J. R. DAVIS AND J. M. HEADRICK

Radar Techniques Branch
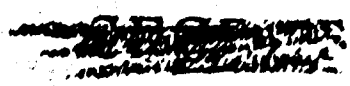*Radar Division*

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November 20, 1964

U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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PREVIOUS REPORTS ON THE PROBLEM

Davis, J.R., Headrick, J.M., and Page, I.H., "A System for the Extension of Unambiguous Radar Range Without Degradation of Velocity Information," NRL Report 5849 (Unclassified Title, Secret Report), Oct 1962

Davis, J.R., "Range Ambiguity Reduction in the Madre Radar," NRL Memo Report 1444 (Unclassified Title, Secret Report) July 1963
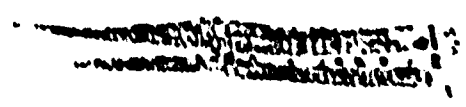
Davis, J.R., "Range Ambiguity Reduction in the Madre Radar, Part II – Initial System Evaluation," NRL Memo Report 1500 (Unclassified Title, Secret Report) Jan 1964

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CONTENTS

ABSTRACT
[Secret]

The Madre radar, a coherent, moving-target-indicating (MTI) radar which utilizes high-frequency ionosphe-ic propagation to extend its range beyond the geometric horizon, has been used repeatedly for tracking aircraft targets at ranges as great as 2000 nautical miles and for detecting launch-phase ballistic missiles from the Atlantic and Pacific missile ranges. A method has been devised by which range ambiguity in the Madre radar may be reduced without that degradation of echo doppler coherence which results from a simple interpulse frequency-shifting method. This new method utilizes a series of double-sideband pulses, with side-bands separated by different intervals from a common supp. essed carrier. These pulses are transmitted cyclically. A description of the double-sideband frequency-shifting system which has been constructed at NRL is given, and its evaluation in a study of local and over-the-horizon aircraft targets is presented. Recommendations for the development of a second-generation frequency-shifting system are made, and suggestions for further study in the range ambiguity reduction problem are also presented.

This is a final report on the problem of range-ambiguity reduction in the Madre radar system. Much of the design, development, and evaluation information in this report appears in earlier publications.

PROBLEM STATUS

This constitutes a final report on all phases of the problem. The problem will be considered closed 30 days after the issuance of this report.

AUTHORIZATION

REDUCTION OF RANGE AMBIGUITY IN THE MADRE RADAR

FINAL REPORT
[Unclassified Title]

INTRODUCTION

A means of achieving high range-rate resolution in a moving-target-indicating (MTI) radar without the use of complex and extensive banks of extremely-narrow-bandwidth doppler filters has been suggested by Page (1). This suggestion is based upon the pulse-doppler principle in which samples of coherent echo pulses are stored over a period of time consistent with the desired range-rate (or doppler) resolution. The use of a rotating magnetic drum for the storage of echo pulses permits pulse-doppler information to be stored for a chosen time interval and then analyzed by a single scanning doppler filter through which stored information may be read off the magnetic drum.

The Radar Techniques Branch, in conducting a long-term investigation of radar signal-processing methods, has developed an experimental radar system in which a signal-processing technique based upon Page's suggestion is implemented. This research radar system, designated the Madre radar, makes use of ionospherically propagated high-frequency (hf) waves to extend its range beyond the geometric horizon.

The Madre radar has been conceived of as a long-range MTI detection system designed to explore the possibilities of detecting and tracking rapid aircraft targets at great distances. The extremely-low-amplitude echoes received from such remote targets are analyzed with the use of a cross-correlation technique based upon the pulse-doppler principle mentioned above. Such operations as the detection and tracking of aircraft targets at ranges of 2000 naut mi (2-5) and the detection of launch-phase guided missiles from the Atlantic Missile Range at altitudes below 100 km (6-11) have been performed repeatedly. The Madre radar has even been effective in tracking aircraft targets as remote from the radar site as 2500 naut mi and in detecting launch-phase guided missiles from the Pacific Missile Range as well (12).

A substantial degree of flexibility has been built into the Madre radar, and this flexibility has permitted the Madre system to be used successfully in many diverse ionospheric radio propagation experiments. It has been useful in performing studies of high-altitude nuclear explosions (13-14), solar eclipse effects upon the ionosphere (15), radar echoes from the moon (16-17), and ionospheric cross-modulation phenomena.

BACKGROUND AND SYSTEM PARAMETERS

In the existing Madre facility, use is made of a recording scheme in which sampled echo pulses are sorted into 23 range intervals and impressed upon a magnetic drum. The system provides storage for 20 seconds of received information at the 180-pulse-per-second (pps) information rate at which the system operates. The drum storage information is continuously modified by the replacement, during each interpulse period, of the oldest information stored upon it. Operating at the design pulse repetition frequency (prf) of 180 pps, the Madre radar provides a presentation of a maximum unambiguous range of 455 naut mi and a range resolution of approximately 20 naut mi. Parameters of the Madre radar which are pertinent to the discussion to follow are summarized in Table 1.

Table 1
Parameters of the Madre Radar

Frequency Band	13.5 to 27 Mc/s
Peak Power	4.6 Mw
Average Power	100 kw
Pulse Repetition Frequency (prf)	180 pps
Pulse Shape	cosine squared

Two antennas are at present available to the Madre radar. A fixed broadside array, consisting of two stacked rows, each of which contains ten dipoles in corner reflectors, is directed toward the east and may be steered electrically over a 60-degree arc in azimuth. This antenna provides a directivity of approximately 29 db over an isotrope at 27 Mc/s. A rotatable array of two dipoles in a corner reflector provides a directivity of approximately 21 db over an isotrope at 27 Mc/s, and it may be steered mechanically to any azimuth.

The use of the Madre research radar to study targets at ranges as great as 2000 naut mi presents an obvious range ambiguity problem: target echoes from several 455-naut-mi range intervals are superimposed upon the display. Although it is often possible to remove most of this ambiguity by studying the range intervals from which ground-backscatter returns are received (at a temporarily reduced prf), ground-backscatter echoes frequently are received from intervals which extend over more than 1000 naut mi in range. Under this circumstance range ambiguity cannot be totally removed by observing ground-backscatter ranges, and the common existence of second- and third-hop backscatter components at widely different ranges complicates the picture further. An obvious expedient is to make a permanent reduction in the system information rate, but the ambiguity thereby introduced into velocity determination is unacceptable in view of the high velocities of the aircraft and missile targets for which the Madre radar is intended.

An equally troublesome source of difficulty in the operation of the Madre radar is the presence, on the display, of returns from targets not actually beyond the geometrical horizon. Such targets as locally operating aircraft and patches of meteor ionization in the local ionosphere continuously obscure the presentation and, indeed, are often of such amplitude as to saturate the analysis system and to render actual over-the-horizon targets undetectable.

One possible method for eliminating range ambiguity without a reduction in prf involves altering the transmitted frequency between pulses and sorting the target returns into separate receiving systems. This method of frequency shifting between pulses imparts a pulse-to-pulse incoherence to the doppler information carried by the different frequency echoes, and hence the analysis system cannot provide the full processing gain which it provides with a coherent pulse-doppler signal. In brief, each echo corresponding to a different transmitted frequency actually conveys doppler information which is entirely independent of the other returns. The system then merely furnishes data from a number of these separate radar signals, the number being equal to the number of different frequencies used. Each different frequency transmission then provides its information at the system information rate divided by the number of frequencies in use. Thus the same degradation of the available unambiguous doppler information results from this method as would result from simply reducing the pulse repetition frequency.

In order to avoid the loss of available doppler sensitivity and yet reduce the penalty in range ambiguity which results from the use of a high prf, a means is necessary to provide pulse-to-pulse doppler coherence between all transmitted pulses. This coherence may be provided by stepping in frequency between pulses in such a manner that all doppler information is referred to a single reference frequency. If a series of double-sideband pulses is generated, with adjacent pulses made up of sideband pairs separated by different amounts from a single suppressed reference frequency (or carrier), all doppler information may be referred to the carrier itself. The pulse-to-pulse doppler coherence necessary to make use of pulse-doppler processing is then provided, and the available doppler sensitivity is preserved. The number of different double-sideband pulses contained in the transmitted pulse sequence determines the order by which system range ambiguity is reduced. A somewhat more detailed development of the double-sideband suppressed-carrier (DSSC) technique appears in the Appendix.

DSSC SYSTEM OPERATION

It was decided to utilize a frequency-stepping scheme in which a set of three DSSC pulses, spaced about the suppressed center frequency at intervals of ± 10, ± 20, and ± 30 kc/s, is transmitted cyclically. An effective fourth sideband pair could be provided simply by transmitting a pulse at the actual center frequency as a fourth step in the sequence. The choice of a three-pulse sequence extends the unambiguous range of the Madre radar to 1365 naut mi and thus provides an unambiguous presentation of the full range extent of normal ground backscatter. In addition, clutter due to locally operating aircraft and meteor ionization patches is superimposed on the 1365-1820 naut mi range interval, leaving uncluttered the range intervals in which both the Atlantic and Pacific Missile Ranges appear and permitting unobscured observation of aircraft targets as far as 2730 naut mi.

Figure 1 is an azimuthal equidistant projection centered on Washington, D.C., and shows shaded the range intervals in which target echoes are obscured by local clutter. It should be mentioned that a two-step or four-step frequency-shifting cycle may be exploited to move the cluttered regions to other range intervals if it is desired to observe targets in the shaded regions shown. The uncluttered range intervals are divided into two 455-naut-mi intervals each.

The 10-kc's difference between each of the above-mentioned sideband pairs provides adequate frequency separation for the use of conventional signal filtering techniques, and the full spectral width of the DSSC signal with this separation is in excess of 60 kc/s. A partial objective of the DSSC frequency-shifting study has been to determine whether the ionospheric path permits operation of a coherent pulse-doppler radar with a signal of such bandwidth.

Figure 2 is a block diagram of the DSSC exciter system which was developed for the study described in this report. The 100-kc/s and 1-Mc/s standard signals indicated in Fig. 2 are derived from a single stable crystal oscillator, and all local oscillator frequencies (LOF), except the final variable frequency oscillator (VFO) signal, are in turn derived from these two standard signals. This use of a common reference for all LOFs insures that the individual double-sideband components remain coherent even though they are processed in separate channels during certain operations in the receiving system. The three crystal oscillators in Fig. 2, operating at frequencies of 510, 520, and 530 kc/s, are the sources of the three DSSC signals. These separate crystal oscillator frequencies are combined into repetitive three-step sequences in the sequential modulators, whose operation may best be understood with reference to Fig. 3.
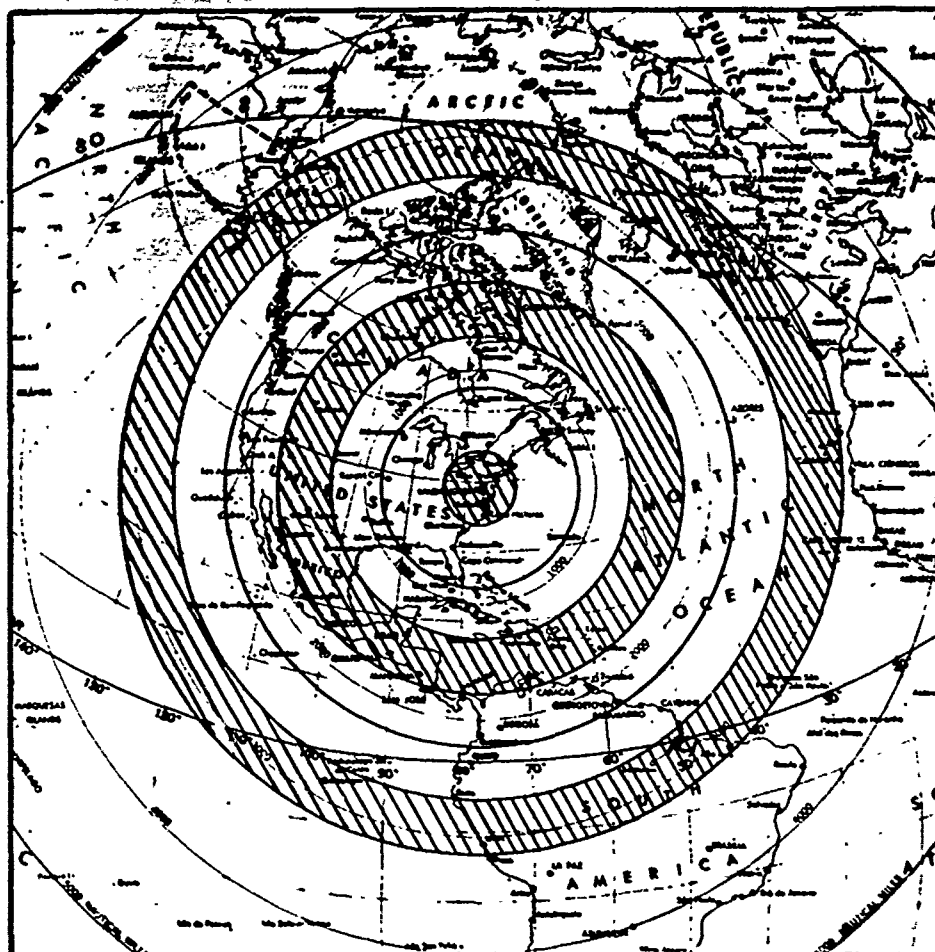
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Fig. 1 - Equidistant azimuthal projection map centered on Washington, D.C. Shaded areas indicate range intervals from which target echoes are obscured by local clutter. The uncluttered range intervals are divided into two 455-naumi intervals each.
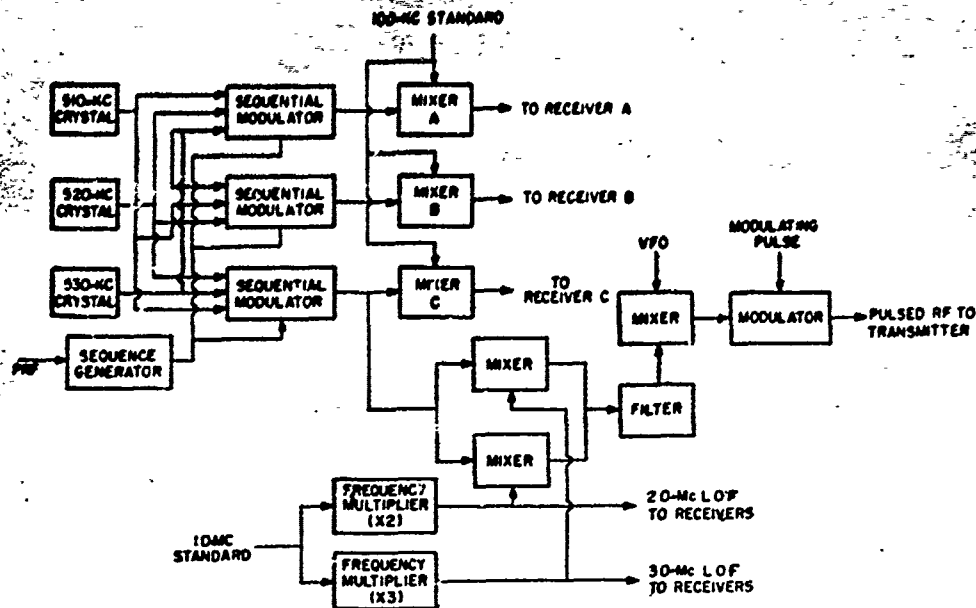
Fig. 2 - Block diagram of the DSSC exciter system.
The three crystal oscillators at the left are the
sources of the three DSSC signals.
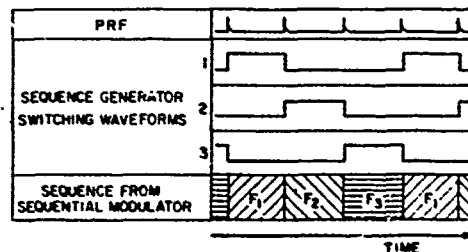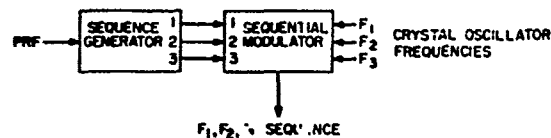

Fig. 3 - Block diagram of the sequence
generator and one of the three sequen-
tial modulators shown in Fig. 2   The
generator produces a three-step switch-
ing sequence which is sent to the modu-
lator. The individual waveforms for
these three steps, and the resultant "on"
or "off" characteristic of the combined
waveforms, are schematically indicated
for one cycle of the operation.

The system prf of 180 pps is used by the sequence generator in Fig. 3 to construct three different three-step switching or gating signals, each with one interpulse interval on and two interpulse intervals off, as illustrated schematically at the bottom of Fig. 3. These three three-step switching signals are applied as gating waveforms to the sequential modulators, each of which has a separate input channel for each of the three crystal oscillator signals and a channel for one of the three sequence generator waveforms, and a single output channel for the three-step sequence of crystal oscillator frequencies created by applying the three gating waveforms to the three crystal oscillator signals (see Fig. 2). Each sequential modulator may be used to obtain the three-step crystal oscillator frequency sequence in a different order.

One of the three sequential modulator sequences is used to create the DSSC signal with the use of the balanced modulator circuit illustrated in Fig. 4, and a signal derived from this same sequence is used in the receiver to provide the LOF sequence necessary for receiver sensitivity to the first 455-naut-mi range interval. The remaining sequential modulator outputs are used to provide the LOF sequences necessary for second- and third-range-interval receiver sensitivity (see Fig. 2).

The operation of the balanced modulator circuit may be understood with reference to Fig. 4 and the following explanation. The three-step sequence of frequencies delivered by a sequential modulator at Point A in Fig. 4 may be represented in shorthand form by

$$(f_1, f_2, f_3) = (510 \text{ kc/s}, 520 \text{ kc/s}, 530 \text{ kc/s}).$$

This sequence is combined in one mixer with a 2.0-Mc/s reference to create   ·quence at Point B_1, denoted by

$$(2.510 \text{ Mc/s}, 2.520 \text{ Mc/s}, 2.530 \text{ Mc/s}),$$

and it is combined in a second mixer with a 3.0-Mc/s reference to create a sequence at Point B_2, denoted by

$$(2.490 \text{ Mc/s}, 2.480 \text{ Mc/s}, 2.470 \text{ Mc/s}).$$

The sum frequencies in the former channel and difference frequencies in the latter channel are selected by a sharp bandpass filter, and the resultant DSSC sequence (2.5 Mc/s ± 10 kc, 2.5 Mc/s ± 20 kc, 2.5 Mc/s ± 30 kc) at Point C is provided to a final mixer in which a VFO reference is utilized to raise the DSSC sequence to the desired transmitting frequency band.

The individual sequential modulator outputs in Fig. 2 are subjected to an additional frequency translation of 100 kc/s in mixers A, B, and C of Fig. 2, whereupon they are provided to the three DSSC receivers for use as local oscillator signals.

The output of mixer C in Fig. 2, which is in the same sequence as the DSSC signal provided to the transmitter, is used as an LOF in the receiver which is sensitive to information from the first 455-naut-mi-range interval. The outputs of mixers A and B are delayed by one and two pulse intervals, respectively, from the sequence provided to the transmitter and hence may be used as local oscillator signals in the receivers which are sensitive to information from the second and third range intervals.

A block diagram of a typical DSSC receiver is shown in Fig. 5. The first two mixing operations in the receiver are the inverse of the two final mixing operations in the exciter. The third mixing operation (in mixers 3a and 3b) makes use of the frequency-translated sequential modulator outputs to create a pair of signals at the 100-kc/s level which display
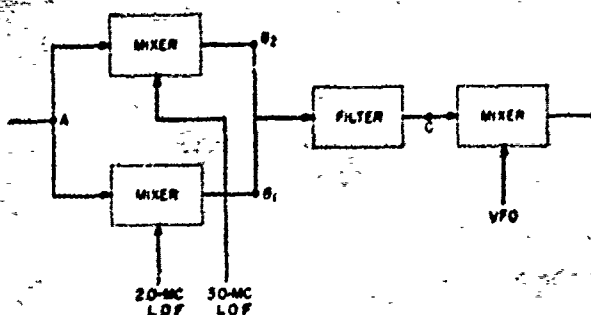
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Fig. 4 - Block diagram of the balanced
modulator circuit used to create a DSSC
signal from one of the three sequential
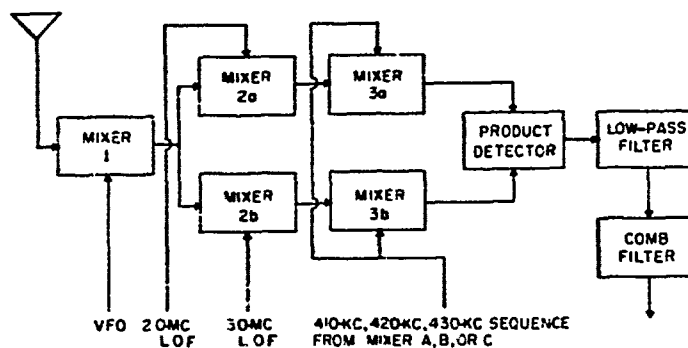modulator sequences (see Figs. 2 and 3)

Fig. 5 - Block diagram of a typical DSSC receiver.
The product detector and low-pass filter remove all
frequency components except those due to the
doppler-frequency cross terms.

doppler-shifted echo information on opposite sides of the 100-kc/s carrier frequency. These
two signals are combined in a product detector and filtered to remove all components
except that due to the doppler-frequency cross terms from the two input signals. The
product detector output then is subjected to a delay-line cancelling (comb-filtering) oper-
ation in which the signal components within a few cycles per second of the center frequency
and the harmonically-related multiples of the prf are strongly attenuated. The resulting
audio signal may then be applied to the Madre analysis system for further processing.

It should be acknowledged that due to the effective doubling of doppler frequency
information which comes about because of the product-detection process in the final
receiver stage, the full unambiguous available doppler of the present Madre radar is not
preserved in the DSSC system. However, a prf of twice the 180-pps rate used in the
present Madre facility could be used with a six-step DSSC frequency shifting sequence to
preserve the full unambiguous available doppler. Indeed, no increase in average power
would be required over the level generated with the present single-frequency Madre sys-
tem by doubling the prf and using the DSSC system. This is because the DSSC exciter

produces a pulse which reaches full peak power with approximately one-half the pulse power contained by a single frequency pulse. Since the existent data processing equipment is operable only at information rates of 180 cps and its binary fractions, the first-generation DSSC system study has been performed using existent equipment with the understanding that the available doppler spectrum is not being fully preserved.

DSSC SYSTEM COMPONENTS

A few remarks concerning the electronic circuits and filter networks used in the DSSC exciter and receiver systems are appropriate. Straightforward design techniques were utilized throughout the development process, and class A triode and pentode amplifiers were used exclusively. A brief description of the techniques used in each of the components that were designed specifically for the DSSC study now follows.

Each of the frequency multipliers (see Fig. 2) consists of a pentode, which is driven at cutoff, followed by a capacitor-coupled single-tuned triode amplifier, and two transformer-coupled triode amplifier stages. Mixers A, B, and C (see Fig. 2) are all simple suppressor-grid-driven pentode mixers, followed by stagger-tuned pentode amplifier stages tuned to equalize the response of the circuit to signal components at 410, 420, and 430 kc/s. The balanced modulator circuit (see Figs. 2 and 4) consists of a pair of single-tuned capacitor-coupled suppressor-grid-driven pentode mixer stages, followed by a bandpass filter centered on 2.5 Mc/s, a transformer-coupled pentode amplifier, and a double-tuned capacitor-coupled pentode amplifier. The bandpass filter (see Fig. 2) is a wideband crystal filter with a 3-db bandwidth of 60 kc/s and a 60/6-db shape factor of 2.5, designed and manufactured by a commercial firm. The final mixer (see Fig. 2) is a capacitor-coupled suppressor-grid-driven pentode mixer stage, followed by a single-tuned transformer-coupled pentode amplifier. The sequence generator, sequential modulators, and pulse-forming modulator (see Figs. 2 and 3) are all adapted from Madre equipment of an earlier design.

The receiver (see Fig. 5) is largely an adaptation of an earlier NRL Madre receiver design in which two single-tuned pentode rf amplifier stages are followed by two suppressor-grid-driven pentode mixer stages (mixers 1, 2a, and 2b) and a pair of cathode-driven triode mixers (mixers 3a and 3b). The product detector is composed of a pair of cathode followers driving a third triode which shares its cathode resistor with the two cathode followers. The low-pass filter is a cascade of three RC L-sections.

The major difficulty encountered in the design of the DSSC exciter and receiver systems has stemmed from the necessity for precise balance in the levels of (a) the two sidebands which compose each DSSC pulse and (b) the three DSSC pulses which make up the pulse sequence. Indeed, improper balance in the levels of the three DSSC pulses, plus substantial imbalance of the LOFs used in the receiver, has been a continual source of difficulty in operating the system. The 60-cps modulation which results from such imbalances often causes a serious degradation in the doppler-ambiguity-elimination characteristics of the DSSC technique.

The DSSC signal is subjected to several mixing operations in the receiver where tuned circuits discriminate against spectral components which are farthest from the center frequency, and the local oscillator levels must be adjusted to compensate for this discrimination. It has, in practice, been impossible to remove all traces of 60-cps modulation from the DSSC system output signal, but enough progress has been made toward eliminating this difficulty so that it is believed to be well within the limits of technical feasibility. In the design of any second-generation DSSC system, considerable attention should be devoted to eliminating the effects of this modulation upon the period of the frequency-shifting cycle of the output information.

A second, although substantially less troublesome, difficulty was encountered in the use of separate crystal oscillators for generation of the three double-sideband signals used in the DSSC study. Because the three crystal oscillators operated independently and were not locked to the system prf, their independent drifts in frequency imparted additional low-frequency modulations, at different frequencies, to the received information. This difficulty could easily be eliminated in a second-generation system by phase-locking the three oscillators to the system synchronization signal.

Figure 6 is a photograph of the DSSC exciter and receiver systems. The rack on the left in Fig. 6a contains the receiver components, which are illustrated schematically in Fig. 5, plus power supplies for the entire DSSC system. The rack on the right in Fig. 6a contains components of the DSSC exciter system, which is illustrated schematically in Fig. 2. Figure 6b is a back view of these same racks. The rack on the left in Fig. 6b contains additional components of the DSSC exciter system, which is illustrated schematically in Fig. 2. The rack on the right in Fig. 6b contains several amplifiers and attenuators used with the DSSC system.

In Fig. 7 is shown the sequence of actual DSSC pulses, separated by intervals of 10, 20, and 30 kc/s, respectively, from a single suppressed center frequency f_c. This photograph was made with a total pulse width of approximately 300 μ sec.

Figure 8 is a spectrum analysis of the DSSC 300-μsec pulse sequence. It may be seen from Fig. 8 that the frequency crossover between adjacent pulses is depressed by 20 db below each band center. The position of this frequency crossover is strongly sensitive to pulse length, however, and it may be attenuated further by simply widening the pulse if strong target echoes are found to spill over into the improper range intervals. The miscellaneous clutter which appears near the 10-db line in Fig. 8 is largely due to spurious responses in the spectrum analysis setup.

There are also low-level frequency side lobes in the DSSC spectrum which do not appear in Fig. 8 due to their low level and (for the widest separated pair of sidebands) remote separation from the center frequency; these components are associated with the fact that the pulsing waveform used to drive the pulse-forming modulator is only approximately cosine-squared in configuration. The pulsing waveform is, in fact, a critically damped exponential waveform, and it is of necessity terminated after a short interval, giving rise to spectrum sidelobes attenuated by 20 to 30 db below the individual band centers. Figure 9 is a photograph of the approximate cosine-squared pulsing waveform utilized in the Madre radar.

DSSC SYSTEM EVALUATION

The existent Madre high-power amplifier and antenna systems have been found to be readily compatible with the DSSC exciter, despite the 65-kc/s bandwidth of the exciter's signal. Operations have been conducted with the DSSC system at full 4.6-Mw peak power throughout the frequency band from 13.5 to 21.3 Mc/s with no noticeable degradation in transmitter performance.

The DSSC system has been evaluated in a series of measurements which have made use of ground backscatter, meteor ionization patches, local aircraft targets, and actual over-the-horizon aircraft targets beyond 1800 naut mi in range. Figure 10 is a series of Madre display photographs made during an observation period in which a local aircraft was tracked for more than 30 minutes. The display represented in Fig. 10 is a conventional MTI doppler versus range display. Doppler shift appears vertically, with a scale
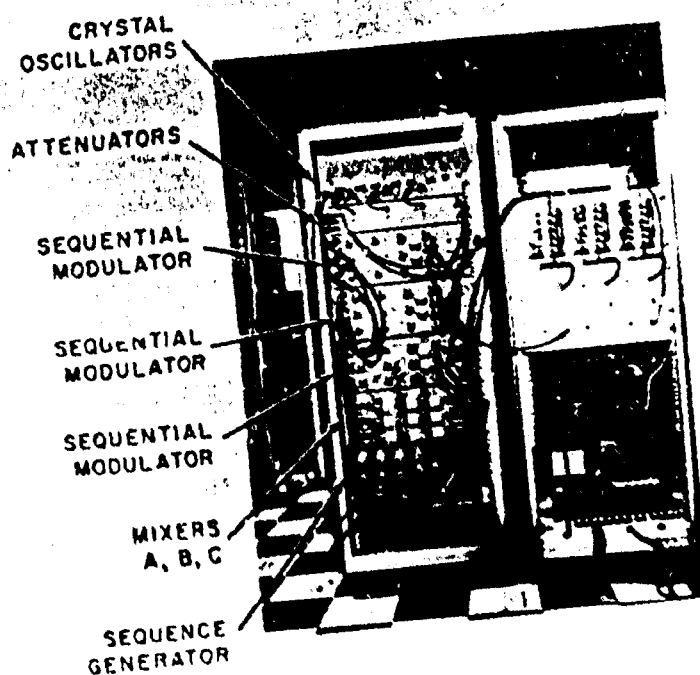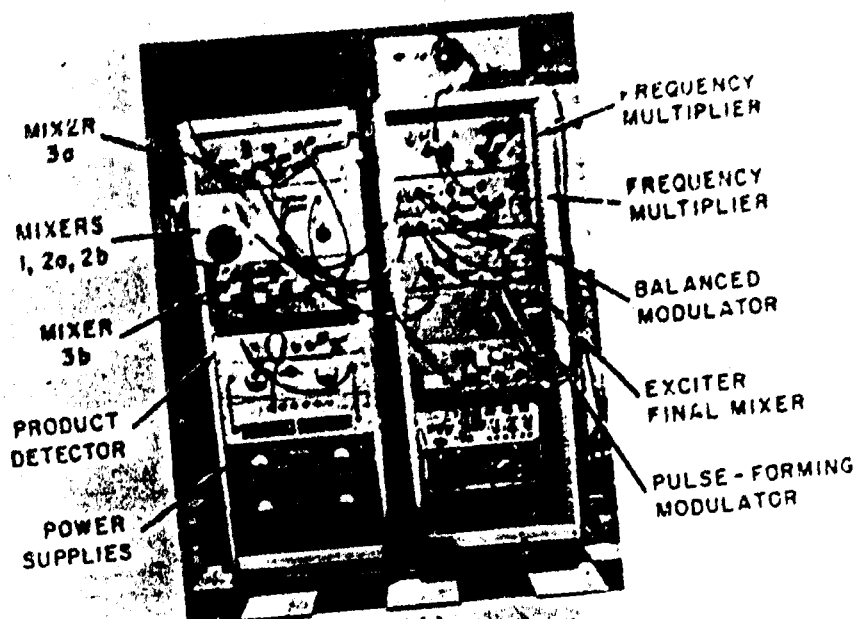
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MIXER
3a

MIXERS
1, 2a, 2b

MIXER
3b

PRODUCT
DETECTOR

POWER
SUPPLIES

FREQUENCY
MULTIPLIER

FREQUENCY
MULTIPLIER

BALANCED
MODULATOR

EXCITER
FINAL MIXER

PULSE - FORMING
MODULATOR

(a)

CRYSTAL
OSCILLATORS

ATTENUATORS

SEQUENTIAL
MODULATOR

SEQUENTIAL
MODULATOR

SEQUENTIAL
MODULATOR

MIXERS
A, B, C

SEQUENCE
GENERATOR

(b)

Fig. 6 - Front view (a) and rear view (b) of DSSC
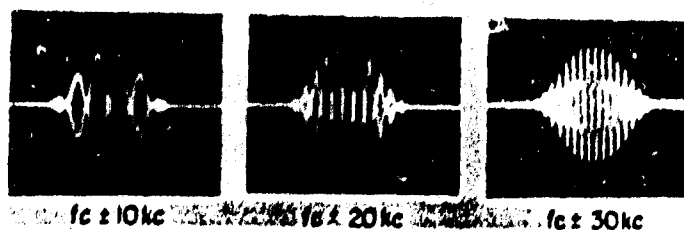exciter and receiver systems

fc ± 10kc   fc ± 20kc   fc ± 30kc

Fig. 7 - Sequence of DSSC pulses separated from center carrier frequency f, by ±10, ±20, and ±30 kc/s. Total pulse width is about 300 μsec in each case.
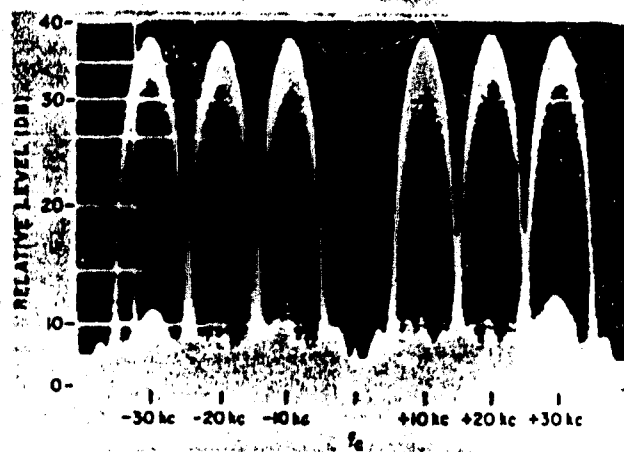

Fig. 8 - Spectrum analysis of the DSSC 300-μsec pulse sequence shown in Fig. 7

Fig. 9 - Cosine-squared pulsing waveform used to drive the pulse-forming modulator which generates the pulses shown in Fig. 8. Because the waveform is only approximately cosine-squared, low-level frequency side lobes are also generated at 20 to 30 db below the individual band centers shown in Fig. 8.
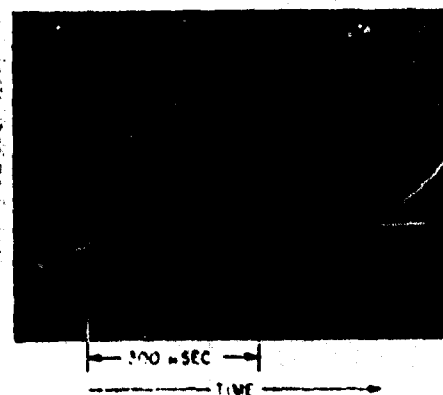
from 0 to 90 cps (0 to 1350 knots) along the left of each photograph. Because no attempt
was made to adjust the doppler scale calibration precisely, the indicated doppler does not
represent the true target doppler. For example, the double horizontal line at approxi-
mately 52 cps on all seven photographs is actually due to 60-cps modulation. The range
is indicated in nautical miles along the bottom horizontal axis of each photograph and the
time (Eastern Standard Time) is indicated below each photograph. During the observa-
tion period represented in Fig. 10, a single pair of sidebands separated by 10 kc/s on
either side of the suppressed center frequency was transmitted; no attempt at stepping
among the three available DSSC pulses was attempted. Furthermore, the receiver level
was adjusted during this period so that over-the-horizon targets were not detectable, and
the receiver comb-filter network was not used. Target echoes in Fig. 10 are circled.
Of the three target echoes in each photograph, the lowest circled trace represents the
actual doppler echo of the target, while the other two redundant circled traces represent
a folding of the target echo about the 60-cps doppler level due to the previously mentioned
spurious 60-cps modulation. The progress of this local target through a decrease of 5 cps
(75 knots) in doppler and 75 naut mi in range may be followed easily. Much of the display
in Fig. 10 is cluttered with traces attributed to spurious system responses. True targets
may be easily separated from these extraneous signals by an experienced operator. A
meteor echo may be seen in the photograph made at 1500 at 300 naut mi in range and
extending from 10 to 20 cps in doppler.

Figure 11 is a series of similar Madre display photographs made during an observa-
tion period in which a true over-the-horizon aircraft target was tracked for more than
15 minutes with the use of the DSSC frequency stepping system. Doppler shift appears
vertically, as in Fig. 10, with a scale from 0 to 90 cps along the vertical axis of each
photograph. The horizontal scale actually represents a range interval extending from
1820 to 2275 naut mi, and the time (Eastern Standard Time) is indicated below each
photograph. The circled trace in each photograph represents the target echo; traces due
to folding about the 60-cps doppler level are also present in several of the photographs
but are not circled. As in Fig. 10, spurious system responses contribute substantial clut-
ter to the display, but the target indicated was tracked continuously for more than 15 min-
utes with no difficulty.

CONCLUSIONS

The first-generation DSSC frequency shifting system described in this report has
demonstrated the feasibility of utilizing the DSSC technique in improving the range ambig-
uity character of a long-range surveillance radar. Several deficiencies have been discov-
ered in the present DSSC system, however, and substantial effort should be devoted in any
future system development to remedying these inadequacies. The specific developmental
needs are:

a.   A precise balance in level must be maintained among the component pulses of the
DSSC frequency-shifting sequence in order to avoid signal modulation at a rate correspond-
ing to the frequency-shifting cycle. This spurious modulation causes a serious impairment
in unambiguous doppler performance of the system and should be eliminated in future
development.

b.   The signals from which the double-sideband pulses are constructed must be prop-
erly related in phase to each other and to the prf to avoid oscillator drifts which contri-
bute a different low-frequency modulation to each of the transmitted DSSC pulses and thus
give rise to a slight pulse-to-pulse doppler incoherence.

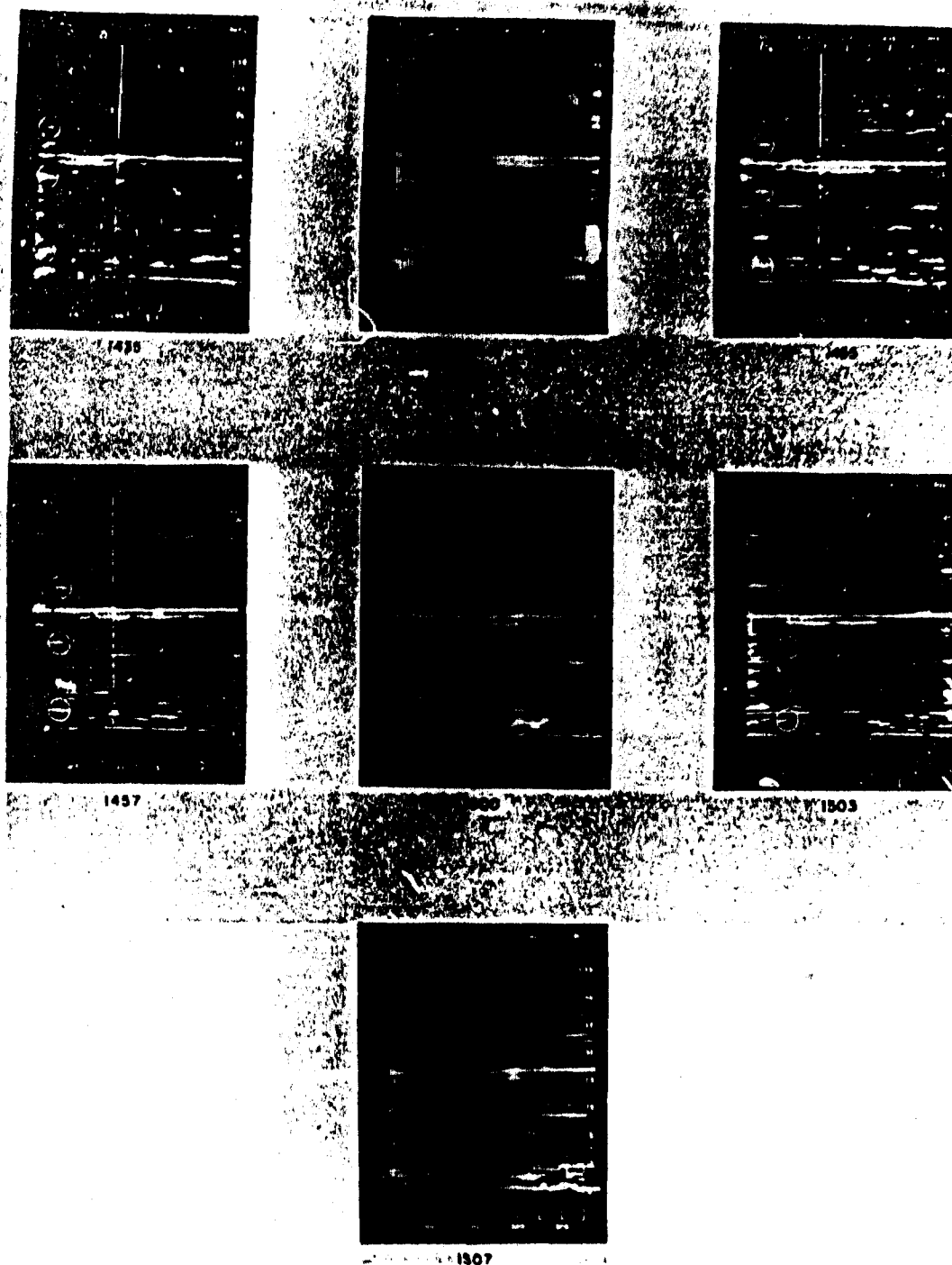   SECRET

Fig. 10 - Typical Madre display of target doppler echo vs target range. A single pair of sidebands separated by 10 kc/s on either side of the suppressed center frequency was transmitted, but no attempt at stepping among the three available DSSC pulses was attempted. The lowest circled trace on each photograph is the true target doppler echo; the other two traces represent redundant echoes of the same target. Left vertical scale is target doppler in cps; bottom horizontal scale is range in naut mi; the time (E.S.T.) is indicated at bottom of each photo.
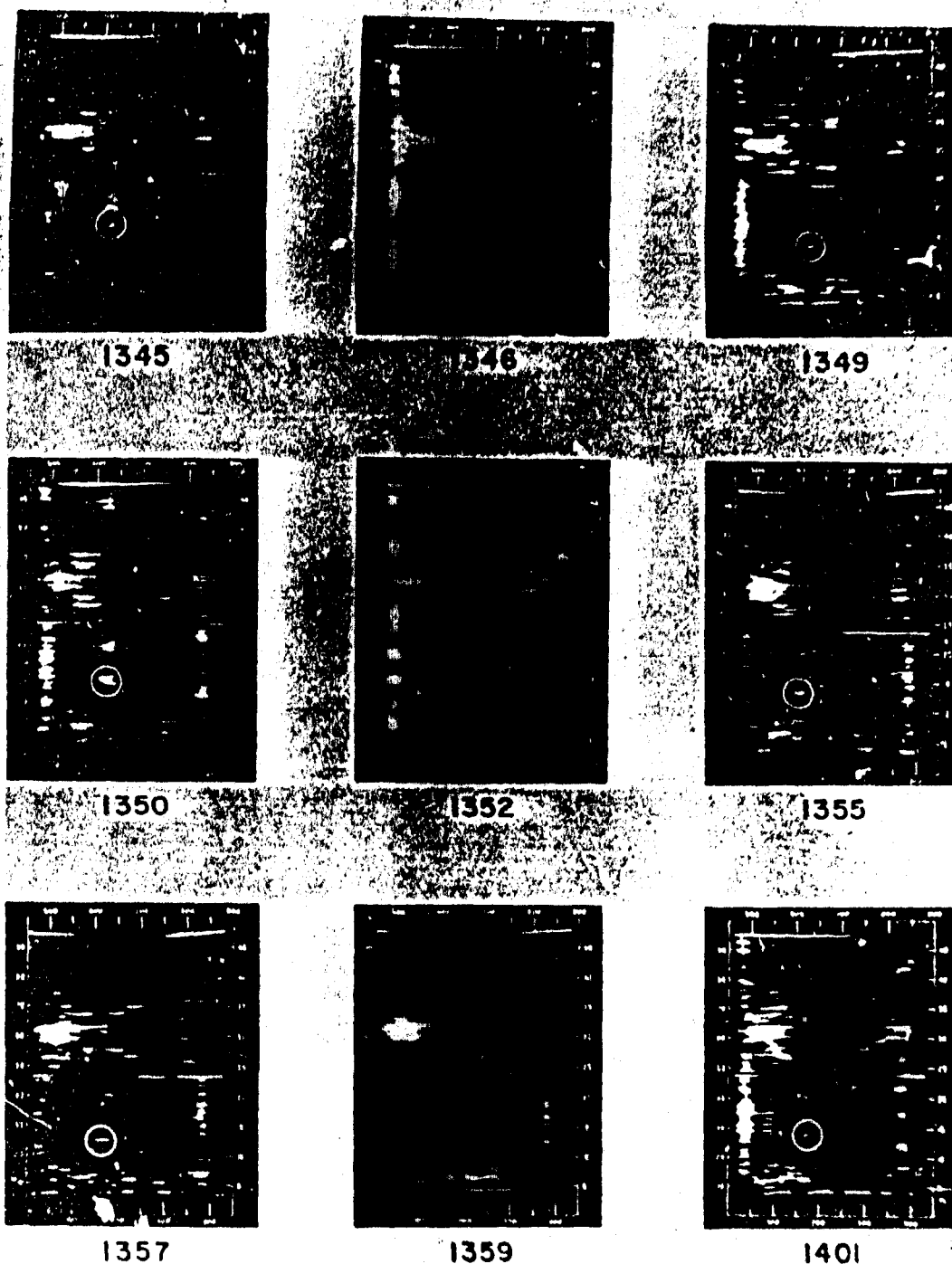
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Fig. 11 - Madre display of an over-the-horizon target obtained with the use of the DSSC frequency stepping system. Left vertical scale is target doppler in cps; horizontal scale is range in naut mi (the range actually extends from 1820 to 2275 naut mi); the time (E.S.T.) is indicated at bottom of each photo

c.   The individual sidebands which compose the DSSC pulses should themselves be single-sideband-like signals, as explained in the Appendix. A substantial improvement in signal-to-noise ratio would result from this sophistication.

d.   The receiver front-end should be split into several narrow-band sections, each with a bandwidth appropriate to one of the individual sidebands of which the DSSC frequency-shifting spectrum is composed. This expedient would contribute a further improvement to signal-to-noise ratio.

There are, in addition, two innate shortcomings, as well as certain advantages, of a frequency-shifting DSSC system which must be weighed heavily in any argument in favor of this method for reducing range ambiguity. These various considerations are:

a.   A DSSC frequency-shifting system requires a rather wide, relatively interference-free channel for optimum performance. The first-generation system described here occupies a frequency band of 65 kc/s, and it is anticipated that a more advanced version would occupy a frequency band as wide as 100 kc/s. High-amplitude radio interference within the band of the DSSC system would be troublesome and could cause a serious degradation in system performance. The over-the-horizon surveillance aspects of the application, toward which this study has been directed, require that the radar be operated within the international hf broadcast bands and, indeed, that it often be operated within the very bands in which traffic is heaviest and in which the likelihood of encountering high-level rf interference is substantial.

b.   A high-power radar in which transmitted energy is spread through a band of frequencies approaching 100 kc/s is not only obnoxious to other users but is rather easily detected and unmistakable in mission to an enlightened listener.

c.   The spread spectrum of such a radar does, however, possess certain advantages with regard to protection against electronic countermeasures (ECM). This aspect is enhanced in importance when it is recognized that the DSSC technique is readily amenable to random frequency-selection methods which would tend to intensify the ECM problem for a hostile listener.

It would be valuable to compare the performance of the DSSC frequency-shifting system with the potential performance of two other somewhat related methods which have been suggested as possible solutions to the range-ambiguity problem. It has been suggested that a radar utilizing two separated frequencies, transmitted at slightly different pulse rates, would provide range information which would be unambiguous to the same order as the length of the period between pulse coincidences of the two transmissions. This technique would, in fact, require a considerably narrower band than the DSSC method (possibly only 20 kc/s as compared to 100 kc/s), but it would require rather complex matched filters to accomplish the range-ambiguity reduction. It is believed that the technical difficulties encountered in this approach would be at least as serious as those which have appeared in the development of the present DSSC system.

Pulse-compression techniques also have been suggested as alternatives to the DSSC frequency-stepping technique. Indeed, the phase-reversal pulse-coding method offers a means of removing range ambiguity and simultaneously permitting transmitter operation at lower peak power. It should be acknowledged, however, that there exist certain difficulties in the use of a phase-reversal technique in hf radar. First of all, as with all pulse-compression systems, complex matched filters must be used in the analysis of received information. (Tapped delay lines are of particular interest in this connection.) Secondly, the use of a long chain of coded pulses instead of a single, comparatively short, high-peak-power pulse in each transmission extends the period in which the receiver must be gated

off for protection against overload due to transmitter leakage. Hence, the blind interva in range which exists around the transmitter pulse, and is repeated at ranges correspo ng to integral numbers of pulse intervals, is substantially extended. It is possible to restrict the frequency band, occupied by an hf radar utilizing the pulse-coding techniqu by using a chain of shaped pulses (like the cosine-squared pulse used with the present Madre radar) to form the coded pulse.

RECOMMENDATIONS

The following recommendations are made:

1. A second-generation system study should be conducted, with emphasis placed implementing the improvements suggested in the above section.

2. A study of random frequency selection should be made, with the aim of develoj ing a technique for selecting DSSC transmitting frequency spectra from a broad range c frequencies. Provisions should be included for (a) automatically avoiding transmission occupied channels, and (b) selecting frequencies with sufficient randomness to intensify the ECM problem for a hostile listener.

3. A thorough study of the phase-reversal pulse-coding technique mentioned in the above section should be made in order to evaluate the technical difficulties to be expect in the use of this method at hf, and perhaps a first-generation phase-reversal system should be constructed and evaluated.

4. A study of noise and interference in 100-kc/s-wide segments of the hf band should be made to determine the feasibility of utilizing portions of the hf band of this width for a radar of the type treated in this report.

5. A study of the transmission bandwidth of the ionospheric path should be made so that the pulse-to-pulse doppler coherence f such wideband signals as are utilized in an hf radar of the type described in this repor. can be evaluated. This study should pro- vide insight into the practical limit on the spectral width which may be useful for such systems.

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APPENDIX

THE DOUBLE-SIDEBAND SUPPRESSED-CARRIER (DSSC) TECHNIQUE

The signal transmitted by a DSSC system may be considered to consist of a pair of sidetones, separated from a suppressed center frequency ω_c by an interval a_k, accompanied by a set of spectral lines separated by the angular equivalent s of the prf and distributed about the two sidetones $\omega_c + a_k$ and $\omega_c - a_k$. Figure A1 is a diagrammatic representation of the spectrum of such a signal.
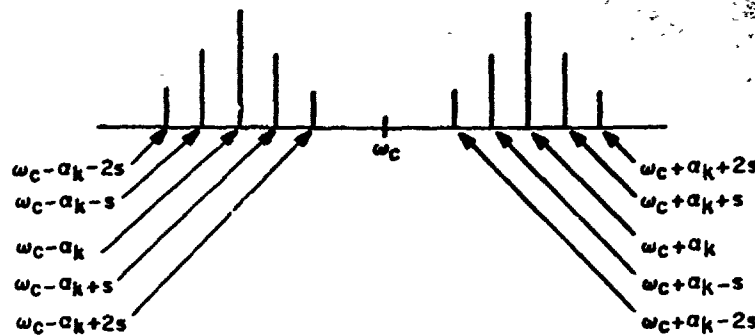

Fig. A1 - Representation of the spectrum of a DSSC signal, consisting essentially of a (suppressed) center frequency ω_c, a pair of sidetones at an interval a_k about ω_c, and spectral lines distributed about the two sidetones by an angular equivalent s of the prf

This signal spectrum may be represented analytically by

$$\sum_{i=-\infty}^{\infty} A_i \cos(\omega_c + a_k + is)t + \sum_{j=-\infty}^{\infty} A_j \cos(\omega_c - a_k + js)t .$$

The index i provides for the harmonically related spectral components separated by the prf angular equivalent s and engendered in the pulsing process. It should be mentioned that the spectral structure represented in Fig. A1 is not an optimum distribution. Slightly less than half of the spectral lines make no contribution to the range resolution toward which the pulsing operation from which they arise is directed. A substantial improvement in signal-to-noise ratio would be made if each sideband of the DSSC signal were itself a single-sideband-type signal. Figure A2 is a sketch of the spectral structure which would result if the DSSC signal were so arranged.

Because the study which this report describes has been conducted with an exciter system in which the redundancy inherent in the former spectral distribution (Fig. A1) is present, the analysis below is directed toward a description of such a system. Both types of systems may be treated similarly, however, and the results of both analyses are fundamentally the same.
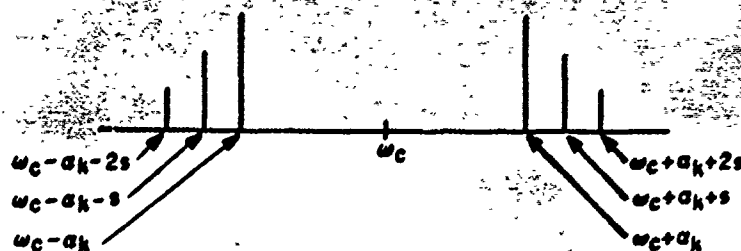
Fig. A2 - Representation of a single-sideband-type signal which might be used with a DSSC system. This particular method represents a substantial improvement in signal-to-noise ratio as compared to the method illustrated in Fig. A1.

The radar echo from an approaching target traveling with a radial velocity may be represented by

$$\sum_i B_i \cos\left[\omega_c + is + a_k + \frac{2v}{c}(\omega_c + is + a_k)\right]t$$

$$+ \sum_j B_j \cos\left[\omega_c + js - a_k + \frac{2v}{c}(\omega_c + js - a_k)\right]t .$$

Upon reception, the echo may be subjected to three simple mixing operations which yield the following resultant signal:

$$\sum_i B_i \cos\left[\delta + is + \frac{2v}{c}(\omega_c + is + a_k)\right]t$$

$$+ \sum_j B_j \cos\left[\delta - js - \frac{2v}{c}(\omega_c + js - a_k)\right]t .$$

The frequency component δ is an intermediate frequency exploited for ease in handling the signal. This signal may then be product-detected, yielding

$$1/2\left\{\sum_i \sum_j B_i B_j \left(\cos\left[2\delta + (i-j)s + \frac{2v}{c}(i-j)s\right]t - \cos\left[(i+j)s + \frac{2v}{c}2\omega_c + (i+j)s\right]t\right)\right\}.$$

The first term in this expression may be removed by appropriate band-rejection filtering, and the remaining term may be subjected to a comb-filtering process which will remove harmonically related multiples of the prf. The final expression, after a convenient change of indices, is

$$\sum_\ell C_\ell \cos\frac{2v}{c}(2\omega_c + \ell_s)t,$$

which is the desired function of the doppler referred to the suppressed center frequency ω_c.

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13 ABSTRACT

The Madre radar, a coherent moving-target-indicating (MTI) radar which utilizes high-frequency ionospheric propagation to extend its range beyond the geometric horizon, has been used repeatedly for tracking aircraft targets at ranges as great as 2000 nautical miles and for detecting launch-phase ballistic missiles from the Atlantic and Pacific missile ranges. A method has been devised by which range ambiguity in the Madre radar may be reduced without that degradation of echo doppler coherence which results from a simple interpulse frequency-shifting method. This new method utilizes a series of double-sideband pulses, with sidebands separated by different intervals from a common suppressed carrier. These pulses are transmitted cyclically. A description of the double-sideband frequency-shifting system which has been constructed at NRL is given, and its evaluation in a study of local and over-the-horizon aircraft targets is presented. Recommendations for the development of a second-generation frequency-shifting system are made, and suggestions for further study in the range ambiguity reduction problem are also presented.

This is a final report on the problem of range-ambiguity reduction in the Madre radar system. Much of the design, development, and evaluation information in this report appears in earlier publications. [Secret Abstract.]

DD FORM 1473 JAN 64

27

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radar systems						
Madre radar						
Range-ambiguity reduction						
Echo doppler coherence						
Frequency-shifting radar						
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interpulse frequency-shifting method. This new method utilizes a series of double-sideband pulses, with sidebands separated by different intervals from a common suppressed carrier. These pulses are transmitted cyclically. A description of the double-sideband frequency-shifting system which has been constructed at NRL is given, and its evaluation in a study of local and over-the-horizon aircraft targets is presented. Recommendations for the development of a second-generation frequency-shifting system are made, and suggestions for further study in the range ambiguity reduction problem are also presented.

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MEMORANDUM

20 February 1997

Subj: Document Declassification

Ref: (1) Code 5309 Memorandum of 29 Jan. 1997
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                  NRL/PU/5230-95-293

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7044, 7051, 7059, 7350, 7428, 7500, 7638, 7655. Add 7684, 7692.

Memo: 1251, 1287, 1316, 1422, ▓▓▓, 1500, 1527, 1537, 1540, 1567, 1637, 1647,
1727, 1758, 1787, 1789, 1790, 1811, 1817, 1823, 1885, 1939, 1981, 2135, 2624, 2701,
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